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115 kV AND 230 kV ARC REACH TESTS AT KLEINBURG OUTDOOR TEST FACILITY

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Low current arc reach tests applicable to 115 kV and 230 kV transmission systems have provided data to relate line length which may be de-energized using live line connectors, to system susceptance. Arc reach, the critical parameter influencing line length which may be dropped, is discussed in terms of radial and horizontal reach, the latter offering the prospects of de-energizing the maximum length of unloaded line for appropriate circuit configurations. A simplified arc reach algorithm is developed to predict conservative arc reach values with charging currents up to 20 A. Assessments of the effects of wind suggest that the longest low current arc reach occurs during conditions with little or no wind.

1.0 INTRODUCTION

On HV transmission systems, taking an unloaded line out of service is often accomplished with the aid of an air disconnect switch, and sometimes with the opening of a jumpered section of appropriate in-line insulators. Naturally, care must be taken to insure that line charging currents do not result in excessively long arcs, especially since arcing is extinguished through elongation and cooling in air. Indeed, as is pointed out in [1], even air break disconnect switches may not be rated to interrupt significant current levels under capacitive charging conditions, with the result that line length must be limited to reduce charging currents so that arc reach does not result in phase-to-phase or phase-to-ground faults which would threaten operator safety or system security.

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Many researchers have investigated arc reach during interruption of long unloaded HV transmission lines [1,2,3,4,5,6,7]. However, for the most part, these studies have been based on the work of Andrews et al [1] who conducted tests thirty years ago with horn gaps to develop empirical relationships between maximum likely arc reach and system voltage and current. Unfortunately, most applicable studies are centred on relatively high currents (50 - 300 A) and must rely on extrapolations to provide insights into arc reach at much lower capacitive currents. To provide better insight into arc reach at lower charging currents, Ontario Hydro initiated in the summer of 1989, a study focused on investigating arc reach resulting from low capacitive current switching.

Ontario Hydro test results at low capacitive currents have provided arc reach data which allowed the development of algorithms to identify line lengths on the 230 kV and the 115 kV systems which can be dropped using live line connectors without exceeding permissible arc reach limits for those systems. Ontario Hydro tests also demonstrate that the effects of wind play an important role in determining low current arc reach. In particular, it is demonstrated that for low current switching, worst case arc reach tends to occur when no wind is present.

A new parameter, Horizontal Arc Reach, has been defined. This supplemental arc reach parameter may find application with specific line configurations, and may allow the isolation of considerably longer lines than is possible if only traditional radial arc reach is used to determine suitable circuit lengths for switching.

2.0 ARC REACH TEST DESIGN

The purpose of the Ontario Hydro arc reach tests was to determine what the maximum probable arc reach might be at capacitive currents between 0.1 and 1.4 A. Part of that determination involved the comparison of Ontario Hydro test data to arc reach values obtained by other researchers using air switches at similar, albeit somewhat higher currents. To achieve these objectives, single phase capacitive current interruption tests were designed to simulate line isolation on both the 115 kV and the 230 kV systems. These tests involved using live line connectors to interrupt single phase capacitive currents at 73 kV (ie. the 115 kV system with 10% overvoltage), and 146 kV (ie. the 230 kV system with 10% overvoltage).

Voltages, capacitive currents, and orthogonal views of high speed videos of the line dropping sequence were recorded during each operation. Measurements of arc reach were made following the procedures outlined by Andrews in [1]. In addition to electrical and physical measurements of the line dropping operation, weather data, including wind speed and direction, were recorded so that the effects of wind on low current arc reach might be investigated.

2.1 Definitions - Radial & Horizontal Arc Reach

Traditionally, researchers have defined arc reach in terms of the arc's extension in any arbitrary direction. For convenience, in this report, that view of arc reach has been designated as *Radial Arc Reach*. Another

potentially useful way of considering arc reach might be to determine the arc reach in the horizontal plane. The premise with this approach to evaluating arc reach is that, sometimes, the nearest grounded object or second phase lies in the horizontal plane away from the arc axis. This view of arc reach has been designated as *Horizontal Arc Reach*, and may be useful for some line configurations in assessing how much line can be dropped.

Radial arc reach has been defined as the distance from a point midway between the arc extremities to the most remote point of the arc at the time of its maximum length [1,3]. The arc reach line is not necessarily perpendicular to the line opener, nor is it necessarily horizontal.

Horizontal arc reach is similar to radial arc reach except that it represents the extension of the arc in the horizontal plane only. Although radial arc reach defines the absolute extension of the arc away from its axis midpoint, this does not give a good measure of the propensity of the arc to spread horizontally from its axis to any nearby object, such as the line support structure, or other horizontally placed phases. Horizontal arc reach is the projection of the arc in the horizontal plane, away from the arc axis, and will generally be less than the radial arc reach.

It is worth emphasizing that arc reach is determined to a great extent by the current being interrupted. During capacitive current interruption, the current is controlled by the line length. Consequently, if the maximum permissible arc reach is considered to be horizontal arc reach, more line may be de-energized without exceeding arc reach limits than if the maximum permissible arc reach is considered to be radial arc reach only.

2.1.2 Arc Reach Limits

Proposed arc reach limits for the 115 kV and 230 kV systems as shown in Table I. The maximum permissible arc reach limits presented in Table I are based on physical considerations, and on the need to limit the arc reach to values which experience has proven to be acceptable to operating staff.

Table I: Arc Reach Limits

System (kV)	Max. Permissible Arc Reach	
	in Feet	in Metres
115	1.5	0.46
230	3.0	0.91

3.0 ARC REACH TESTS AT KLEINBURG

Tests of the interruption of relatively low capacitive currents at 115 kV and 230 kV single phase levels were carried out at Ontario Hydro's Kleinburg test facility to establish arc reach during low current conditions. The results of these tests were used to help establish line lengths which might be dropped without exceeding the Ontario Hydro maximum permissible reach limits.

3.1 The Test Set-up & Data Acquisition

Table II presents the electrical parameters for the line dropping tests at Kleinburg:

TABLE I

Kleinburg Arc Reach Test Parameter Values

System Voltage Class (kV)	System Voltage to Ground (kV)* (switch voltage)	Capacitive Current Interrupted (A)	No. of Current Interruptions
115	73	0.419	21
		0.611	17
		0.803	19
		1.059	18
		1.380	22
230	146	0.111	15
		0.296	11
		0.502	14
		0.633	14
		0.828	20

* System voltage to ground includes a 10% overvoltage from nominal.

The levels of capacitive currents interrupted during this test program were provided by several sections and interconnections of HV lines as well as by the provision of additional capacitances to achieve the desired currents.

A jumpered in-line insulator was used to model a live line opener. When the line was energized at the appropriate voltage, the jumper was opened and an energized portion of line was dropped. Variable capacitive line charging currents were achieved by connecting increasing amounts of line into the circuit, and by adding capacitive loads to the HV test line.

Figure 1 shows the in-line opener system used during these tests, and Figure 2 shows a technician opening the jumper during a test.

The jumpered insulator was opened by triggering a specially designed release latch which allowed the jumper cable to drop away from the insulator and to draw an arc. Figure 3 presents two orthogonal views of one such operation showing two simultaneous views of the arc being drawn. The geometric procedures outlined in [1] were applied to views such as that of Figure 3 for each line dropping operation so that radial and horizontal reaches could be calculated.

Figure 1: The Jumpered In-line Opener

Figure 2: In-line Opener Operation

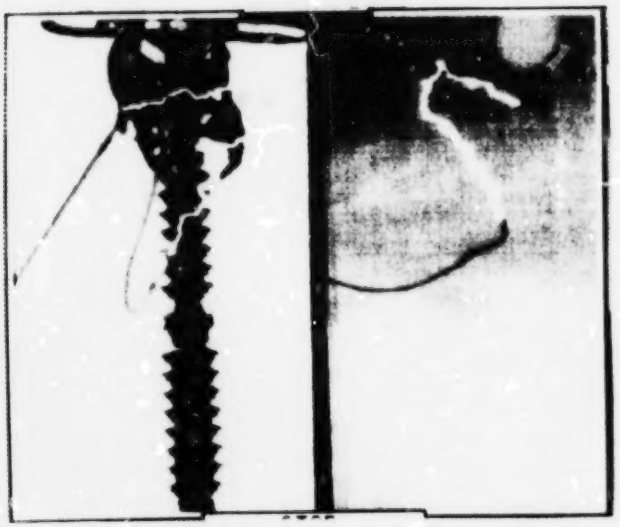

Figure 3: A Typical Arc

3.2 Data Analysis

As with the work of other researchers, in the Ontario Hydro data analysis, arc reach was calculated in terms of (reach length)/kV. This allowed a better assessment of arc reach by de-sensitizing the observed values to particular test voltages.

A statistical approach to data analysis was undertaken. The test data at each current level was analyzed to determine statistical distributions, and to calculate the cumulative probability at each current level. When sufficient numbers of tests at each current level had been done, the data was divided into two groups. The first set of data pertained to arc reach/kV during tests when there was little or no transverse wind to disturb the arc. Generally, when transverse winds were less than 6.5 km/h (4 mph), the data set was designated as having no wind effects. When the wind exceeded 6.5 km/h the data set was designated as having been influenced by wind.

A representative analysis of one data set is presented in Figure 4.

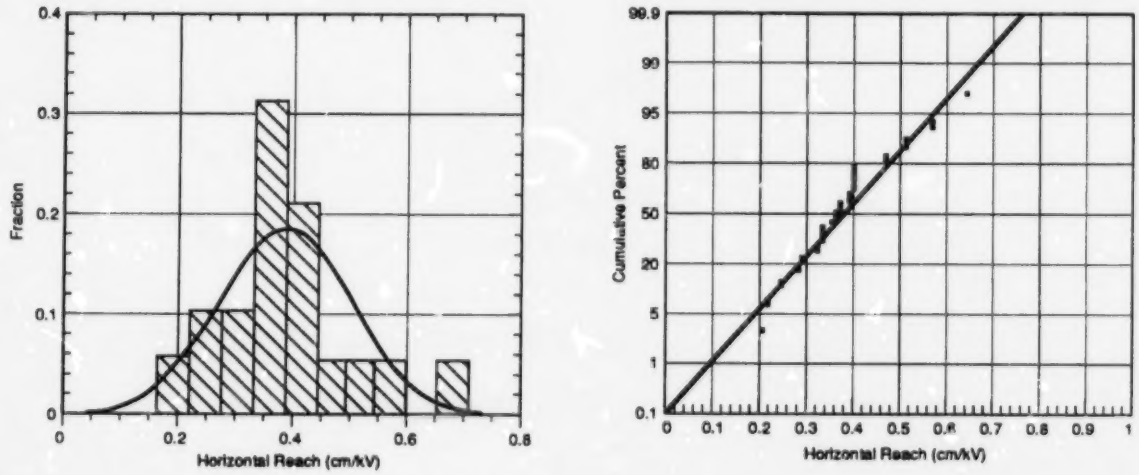

Figure 4: Distribution and Cumulative Probabilities
or One Data Set of Test Values

Traditionally, the maximum arc reach has been determined by drawing a line along the top of the data set, and by designating the equation of that line as the maximum likely arc reach characteristic [1]. This has the inherent liability of defining maximum arc reach values from a finite and often small data set. Little assurance can be offered that the arc reach characteristic accurately represents field conditions. Because the *distribution of arc reaches* is not used with traditional approaches, longer reaches than those predicted by using only the observed data are likely. Moreover, by using only observed values to determine the maximum arc reach, no indication of the probability of achieving limiting reach values is possible.

A better approach to determining realistic maximum arc reach is the use of the cumulative probability characteristic of the data set. While selecting an arc reach characteristic based on the cumulative probability observed with a particular data set does not guarantee that the population of arc reaches has been closely defined, it nevertheless reduces the ambiguity of arc reach predictions by recognizing the particular arc reach distributions observed during tests. Implicit is the assumption that the test data cumulative probability characteristic approximates the cumulative probability characteristic of the population of arc reaches obtained under similar conditions in the field. Thus, the use of the arc reach distribution and the attendant cumulative probability characteristic allows data-based arc reach predictions to selected probability levels.

For each data set obtained during the Ontario Hydro arc reach tests, the statistical distribution and the cumulative probability characteristic was determined. The 99% cumulative probability threshold was selected as an acceptable threshold value to describe the maximum likely arc reach for that data set. In essence this means that for the data obtained during the Ontario Hydro tests, 99% of the arc reach readings were at or below the selected threshold level. The 99% cumulative probability values were then used to describe the maximum arc reach at each current level, and thereby to develop the maximum probable arc reach characteristic.

The maximum probable arc reach characteristic so determined was then compared to a similar characteristic generated using tests data determined by Andrews et al during capacitive switching of a 133 kV line [1]. This was done to illustrate that Ontario Hydro's test results are comparable to and supplement the results obtained by other researchers. Finally, by using the maximum permissible arc reaches defined for Ontario Hydro systems (see Table I), line lengths which might be dropped at lower currents were calculated as a function of line susceptance. This last relationship between line length and susceptance was plotted to allow utility staff to determine, for any line of known susceptance, what line length might be dropped for low current de-energization using live-line connectors.

4.0 TESTS DEMONSTRATE LOW CURRENT ARC REACH

4.1 Kleinburg Test Data Analysis

Figures 5 and 6 present scatterplots of arc reaches/kV measured during low current tests with both wind and no wind effects. In each figure, a line representing the 99% cumulative probability has been drawn. The 99% cumulative probability line intersects the scatterplots at or above the test data maximum values.

The equations for the 99% cumulative probability limit are indicated in each of the above figures. It is worth observing that at low current levels the ranges of arc reach readings are sufficiently wide to prevent the 99% cumulative probability characteristic from reaching zero at zero current. This observation implies that there may be a threshold value of arc reach which is possible, even at very low current values. Put another way, the 99%

cumulative probability characteristic implies that at low currents, if an arc exists at all, some arc reach is possible, and relatively independent of current.

4.2 Analysis of Published data - 133 kV Capacitive Switching at Low Currents

In 1950 Andrews et al presented the values of arc reach measured during switching tests of capacitive current (2.2 to 20 A) on a 133 kV line. Although a detailed analysis of those test results is not presented in the paper, arc reach values and currents are tabulated and therefore allow the application of the analytical techniques presented in this report.

Figure 7 presents the scatterplot of Andrews' arc reach tests on the 133 kV line, along with the 99% cumulative probability characteristic for that data.

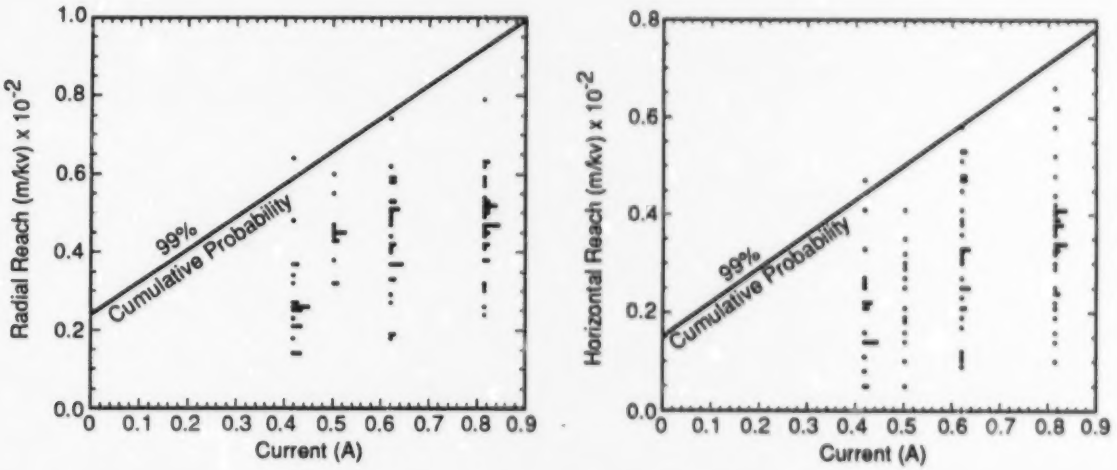

Figure 5: Radial and Horizontal Arc Reach With No Wind Effects

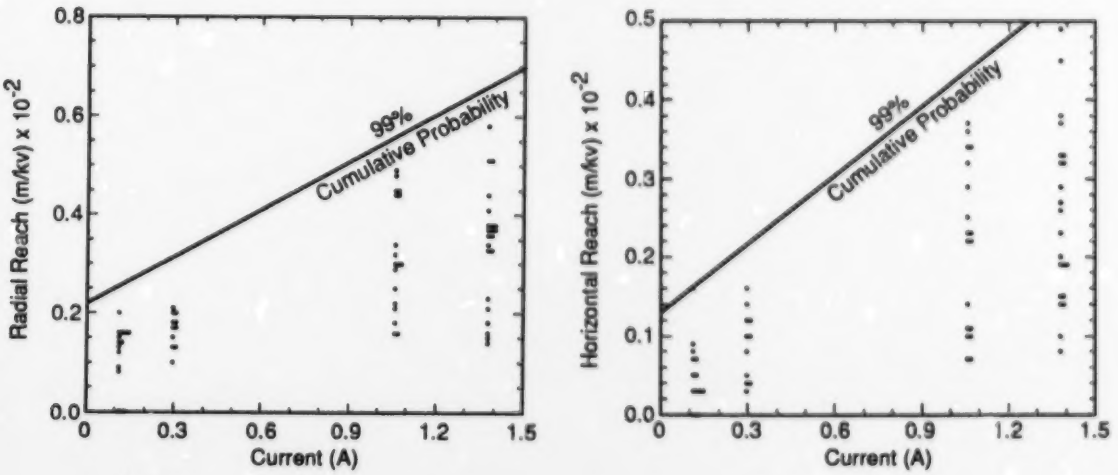

Figure 6: Radial and Horizontal Arc Reach With Wind Effects

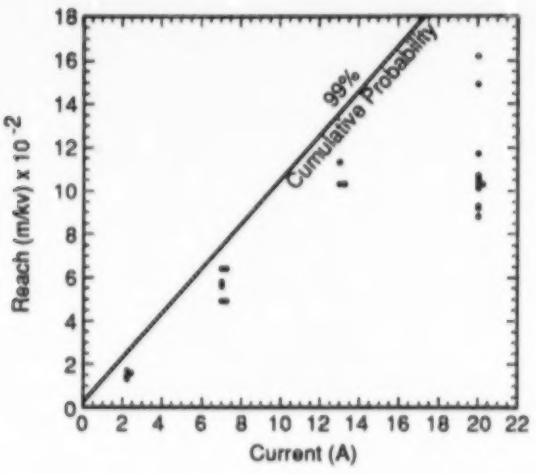

Figure 7: Radial Arc Reach Scatterplot (data from [1])

As with the data from the more recent Ontario Hydro tests, the 99% cumulative probability characteristic presenting the maximum probable arc reach values does not reach zero at zero current. Again, it is apparent that at very low currents, if an arc can be established and maintained, a small maximum probable reach will exist and be independent of current.

4.3 Summary of Test Data

Table III summarizes the 99% cumulative probability characteristics of Figures 5, 6 and 7.

TABLE III

Maximum Probable Arc Reach Equations
(99% Cumulative Probability)

Current Interrupted (A)	Maximum Reach in Metres*				Source
	No Wind		Wind		
	Radial	Horizontal	Radial	Horizontal	
less than 1.4	$\frac{(8.3I+2.4)E}{1000}$	$\frac{(7I+1.5)E}{1000}$	$\frac{(3.2I+2.2)E}{1000}$	$\frac{(2.9I+1.3)E}{1000}$	Kleinburg
2.2 to 20	$\frac{(10I + 3)E}{1000}$				Andrews et al 133 kV line Tests

*Maximum arc reach is the 99% cumulative probability value. "E" is the voltage across the contacts, in this case, the line-to-ground voltage in kV.

Figure 8 presents plots of the arc reach equations of Table III describing maximum arc reach conditions.

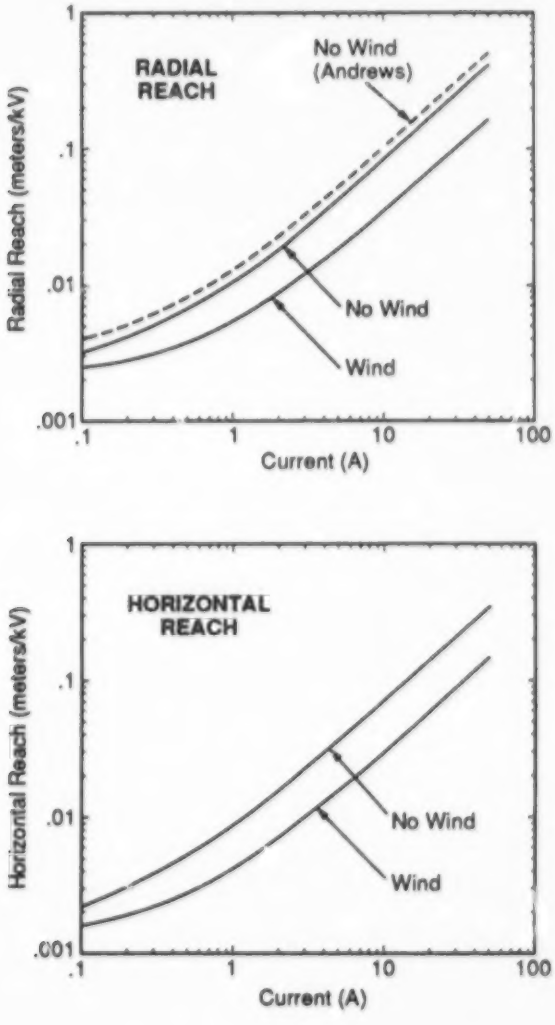

Figure 8: Maximum Probable Arc Reach Plots

The following observations and comments may be made from Table III and Figure 8:

1. The maximum arc reach resulting from very low capacitive currents being interrupted tends to approach a small threshold value. This is brought out by the methods used to define maximum probable arc reach. Even at

very low currents, the measured arc reach values resulted in arc reach distributions. Because the 99% cumulative probability value represents a "near" maximum value possible, it will be offset from zero as long as arc reach values form a distribution. In this case, "near" maximum reach values at very low currents will be between 0.0015 and 0.003 m/kV, and relatively independent of current.

2. The maximum probable horizontal reach tends to be much less than the maximum probable radial reach, particularly at very low currents. This suggests that if horizontal reach is used for comparison to the maximum permissible reach limits, more line can be dropped than has been permitted when only radial reaches were used to determine line lengths which could be switched.

3. At low currents, wind reduces arc reach. One explanation for this observation might be that significant transverse wind cools the arc and helps to extinguish it before long reaches can be attained.

4. Test results obtained by Andrews are consistent with Ontario Hydro test results in that the arc reach characteristic calculated using Andrews test data is only slightly higher than the radial arc reach characteristic determined using Ontario Hydro data. Since wind can have a significant effect on arc reach, it is likely that the Andrews' test data was taken during times when there was no wind, and as a result, produced slightly higher values of arc reach. However, this aspect of arc reach was not fully discussed in [1] and therefore no firm conclusions about wind effects in Andrews data can be drawn.

5.0 SIMPLIFIED ARC REACH CHARACTERISTIC

Low current interruption cannot always be assured and in fact, may not always be practical. For this reason, it would be useful to combine the work of other researchers with Ontario Hydro's Kleinburg test data to develop a simple maximum probable arc reach algorithm which will allow predictions of arc reach at currents up to 20 A.

Because arc reach algorithms resulting from Ontario Hydro tests and similar algorithms resulting from the work of previous researchers are in relatively close agreement, it is feasible to combine Ontario Hydro's and Andrews' test results to provide a simple arc reach characteristic describing maximum probable radial arc reach from 100 mA to 20 A.

This has been done in Figure 9.

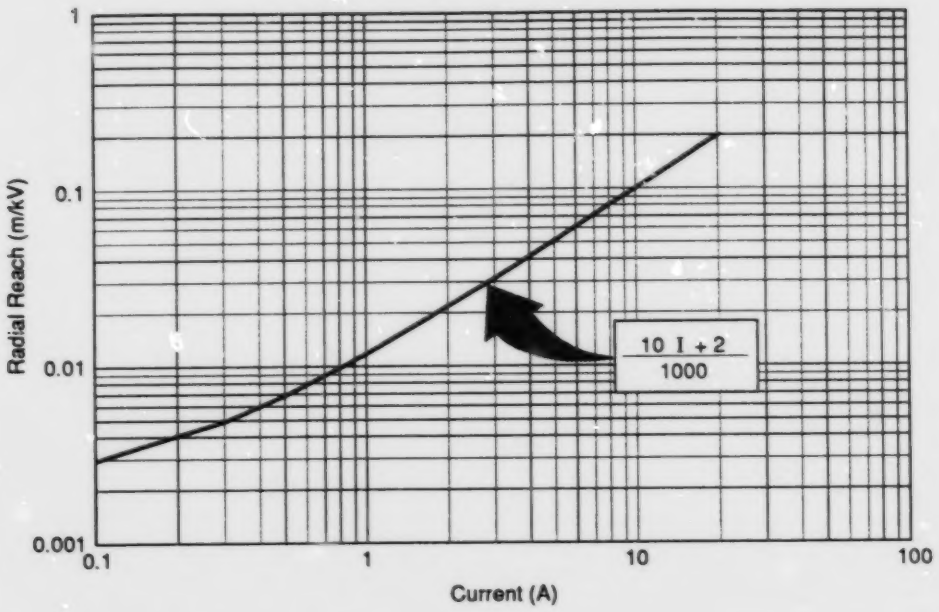

Figure 9: Radial Arc Reach for Interrupting Capacitive Currents (Combined Ontario Hydro & Andrews' Test Data)

In Figure 9, the curve for maximum radial arc reach is formed from the characteristic for radial arc reach determined during the Ontario Hydro tests during "no wind" conditions (ie. the worst case), and from the data provided by Andrews relating to capacitive switching [1].

The curve of Figure 9 is described by the equation in the insert. This relatively simple approximation can be used to very quickly obtain a conservative estimate of the maximum radial arc reach in the current range of 0.1 A to 20 A. By using the 99% cumulative probability arc reach values determined during Ontario Hydro tests, assurances can be offered that the arc reach characteristic of Figure 9 provides a *higher* than 99% cumulative probability for the radial reach.

Figure 10 is similar to Figure 9, except that it presents a curve and algorithm which can be used to quickly estimate horizontal arc reach values in the capacitive current range of 0.1 A to 20 A.

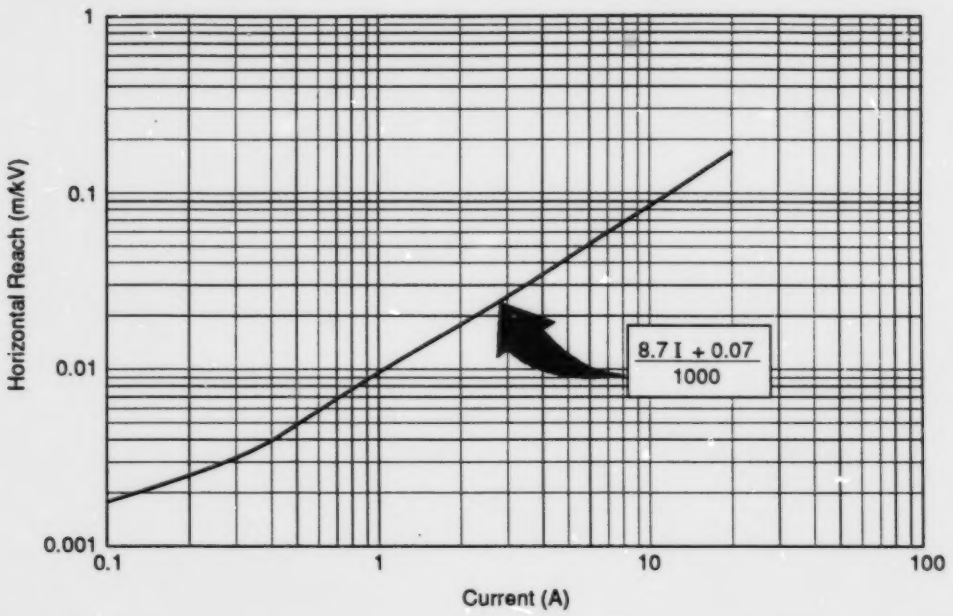

Figure 10: Horizontal Arc Reach for Interrupting Capacitive Currents

6.0 LINE LENGTHS WHICH CAN BE SAFELY DE-ENERGIZED

The arc reach limits of Table I and the "worst case" radial arc reaches of Figure 9, can be used, along with realistic line susceptances, to develop a characteristic for line length which can be safely dropped without exceeding maximum permitted radial reach values. This has been done in Figure 11. The procedure to determine the line length characteristics of Figure 11 is described in the Appendix.

Attempting to drop lines longer than indicated by the characteristics of Figure 11 will result in arc reaches which may exceed permitted values; dropping line lengths shorter than those indicated by the characteristics of Figure 11 will result in tolerable arc reach and in conservative practice.

In most cases, the parameter of greatest interest in determining the length of line which can be switched is the radial arc reach. Horizontal arc reach, as defined in this study, will in all likelihood find application only in a small number of very specific applications. Accordingly, Figure 11 represents radial arc reach only. When circumstances suggest that the distinction between radial and horizontal arc reach might provide an advantage, reference must be made to the specific curves for horizontal reach, and to the procedures in the Appendix to determine maximum line lengths which can be dropped.

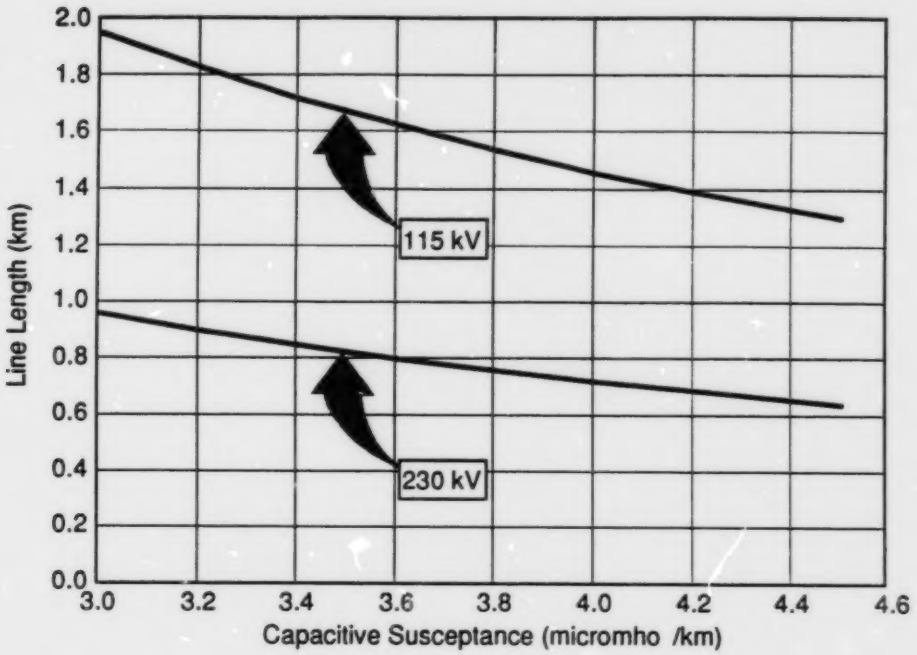

Figure 11: Interruptable Line Length VS Susceptance

7.0 CONCLUSIONS

7.1 Kleinburg test data indicates that, for the 115 kV system, using *radial arc reach* as the measure of reach, from 1.3 km to 1.95 km may be dropped, depending on the particular line susceptance (see Figure 11).

7.2 For the 230 kV system, using *radial arc reach* as the measure of reach, from 0.64 km to 0.96 km may be dropped without exceeding arc reach limits, depending on the system susceptance (see Figure 11).

7.3 Radial arc reach tends to exceed horizontal arc reach by a factor of between about 15% (1.15 pu) and 63% (1.63 pu), depending on the current (see Figures 9 and 10).

7.4 Wind can influence both horizontal and radial arc reach. In both cases, when winds are below about 6.5 km/h, arc reaches tend to be longer, at any current, than when winds are higher.

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APPENDIX

Line Length Calculations

A.1 Governing Equations

From the Ontario Hydro Kleinburg tests with no wind effects (ie. most severe case for arc reach),

$$ {}^{r}R_{cap} = \frac{(10.07\ I + 2)\ E}{1000} \quad \ldots\ldots(1) $$

where ${}^{r}R_{cap}$ is radial reach in metres

E is in kV_{rms}
I is in A_{rms}

and, for any line,

$$ I = \frac{E\ B\ l}{1000} \quad \ldots\ldots(2) $$

where I is line current in A_{rms}

B is capacitive susceptance in micromho/km
l is circuit length in km
E is line-ground voltage in kV

A.2 Arc Reach Limits

Ontario Hydro has defined arc reach limits for the 115 kV and 230 kV systems as shown in Table A-I.

Table A-I: Arc Reach Limits

System (kV)	Max. Permissible Arc Reach in Metres	
in Feet		
115	1.5	0.46
230	3.0	0.91

A.3 Line Length Calculation

A characteristic will be developed describing the line lengths which may be dropped for the 230 kV and the 115 kV systems such that the maximum probable arc reaches produced will not exceed the limits specified by Ontario Hydro in Table A-I.

From equation (1)

$$ I = 99.3\ ({}^{r}R_{cap}/E) - 0.199 $$

From equation (2)

$$l = \frac{1000}{E\ B} I$$

So that

$$l = \frac{1000(99.3(^{r}R_{cap}/E) - 0.199)}{E\ B}$$

$$= \frac{9.93 \times 10^{4}(^{r}R_{cap}/E) - 199}{E\ B} \quad \ldots\ldots(3)$$

For the 115 kV system, $^{r}R_{cap}$ = 0.46 m and E = 73 kV. Then

$$l_{115} = \frac{5.85}{B} \quad \ldots\ldots(4)$$

For the 230 kV system, $^{r}R_{cap}$ = 0.91 m and E = 146 kV. Then

$$l_{230} = \frac{2.88}{B} \quad \ldots\ldots(5)$$

Equations (4) and (5) determine line lengths which can be dropped without significant probability of exceeding the specified arc reach limits. Data from Ontario Hydro's System Planning Division suggests that for the 115 kV system, susceptances lie within the range of 3.04 to 4.4 micromho/km, and for the 230 kV system, within the range of 3.17 to 3.85 micromho/km.

Table A-II presents data defining acceptable line lengths which can be safely dropped for the range of line susceptance of 3 to 4.5 micromho/km.

Table A-II: Line Length (km) which can be Safely Switched

	B (micromho/km)							
	3	3.2	3.4	3.6	3.8	4.0	4.2	4.5
l_{115}	1.95	1.83	1.72	1.63	1.54	1.46	1.39	1.30
l_{230}	0.96	0.90	0.85	0.80	0.76	0.72	0.69	0.64

The data in Table A-II has been plotted in Figure 11.

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